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SOLID STATE GRID MODULATOR

Comprehensive Power, Inc.

Franklin B. Jones

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APPROVED: James M. Van Damme

JAMES M. VAN DAMME
Project Engineer

FOR THE DIRECTOR: Robert G. Polce

ROBERT G. POLCE, Chief
Rome Operations Office
Sensors Directorate

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Franklin B. Jones

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Comprehensive Power, Inc.
28 Hillando Drive
Shrewbury MA 10545

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1 Introduction

This program was for the design, construction, and test of two solid state grid modulators to provide enhanced performance and improved reliability in existing S-band radar transmitters at the Rome research site. Specifically, the modulators support the pulse widths and PRFs needed to mimic the waveforms of the AN/APY-2 AWACS radar transmitter. These include a mixture of long-pulse, low-PRF and short-pulse, high-PRF modes which could not be supported by the transmitters' original grid modulators.

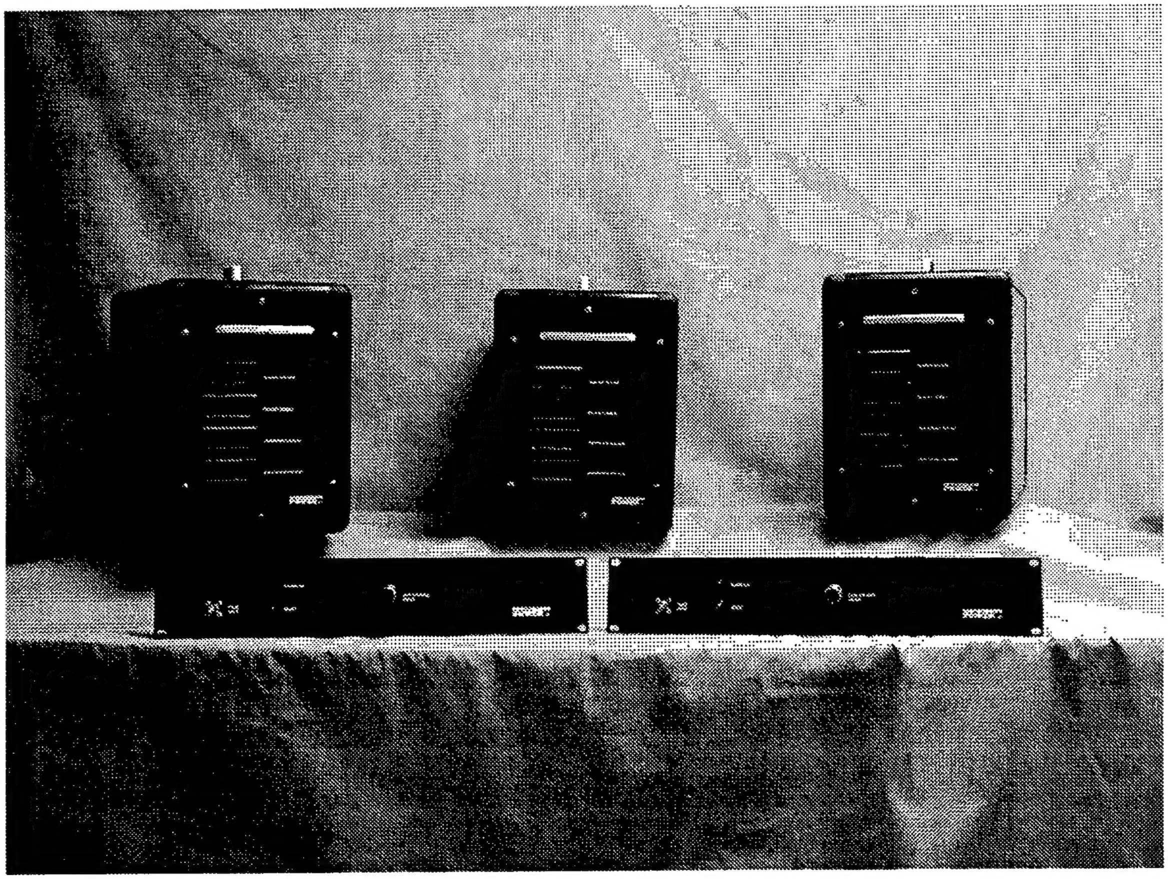

Figure 1-1. Solid State Grid Modulators Delivered to Rome Research Site

The modulators, shown in Figure 1-1 above, were delivered and tested at the Rome research site. Operation was demonstrated under a variety of conditions. The pulsewidth was varied across the specified range. The pulse repetition frequency was varied from zero to maximum. The positive gating was adjusted from zero to maximum. The modulators were subjected to faults including faulty inputs and live short circuits on the output. Each delivered unit was successfully tested.

2 Program Description

The Advanced Airborne Surveillance Program is envisioned as a bistatic adjunct to the E-3 Sentry radar platform. Existing test plans rely on the use of an operational E-3 AWACS system for testing. This is expensive, and relies on the availability of the latest generation E-3. An alternative testing program which uses enhanced existing AFRL radar assets will be far more available and much less expensive. This program began the enhancements required to enable the AFRL Signal Processing Facility to effectively radiate the signals required for an AASP test program.

The existing AFRL S-band radar has two transmitters, each of which uses a VTS-5753 Coupled Cavity TWT. Each TWT is controlled by a grid, which is raised to +450 volts with respect to the cathode to turn the tube on, and lowered to –600 to turn the tube off. The grid must be rapidly switched between the voltages at the rate of the Pulse Repetition Frequency. The existing grid modulators were designed for long pulses at low PRFs, and are not adequate for the high PRF waveforms used by the AWACS.

The new grid modulator is an all solid-state design, consisting of a ground deck, which is connected to chassis ground, and a floating deck, which floats at the cathode potential of 41 kV. The ground deck consists of fiber optic transmitters and receivers to transfer pulse waveform commands and status signals between the ground deck and floating deck.

An isolation transformer provides isolated 120 VAC power to the floating deck. The floating deck includes power supplies for the heater and floating controls. Adjustable positive and negative bias voltage regulators provide tightly controlled low-noise grid drive. Fast ON and OFF switches consisting of series connected MOSFETs provide the required range of PRFs and pulse widths, with pulse rise and fall times set by current-limiting resistors. A spark gap protects the floating deck from grid arcs. An adjustable filament current regulator provides tight regulation and soft starting for the cathode's heater.

The floating deck is housed in an aluminum shell with rounded corners, and is to be mounted on insulators with sufficient clearance from the chassis to stand off the cathode voltage. The ground deck is a separate package that is mounted at ground potential, up to 5 meters from the floating deck. The isolation transformer is to be floor mounted behind the floating deck.

The design of the solid state grid modulators is derived from the approach used on the AFRL C-Band transmitter, developed under contract number F30602-85-C-0219. The present design preserves the desirable features of the C-Band pulser, while making several improvements which are possible because of advances in electronic components over the intervening years.

3 Design Description

3.1 System

A schematic diagram of the transmitter is shown in Figure 3-1. The floating deck is connected to the cathode, heater, and grid of the TWT, and floats at the cathode voltage.

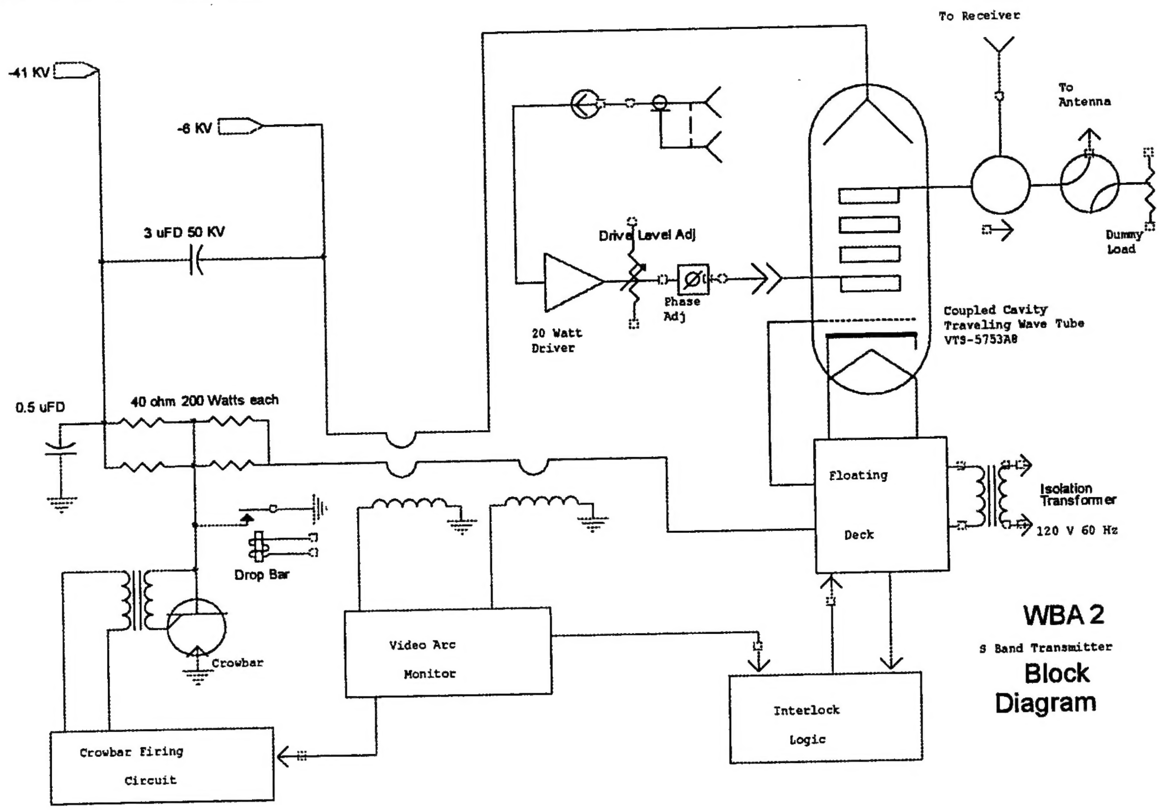

Figure 3-1. Transmitter Schematic Diagram

A schematic of the Solid State Grid Modulator, SCH 1152 Rev A, is on the following page. The schematic shows the ground deck pulser, the floating deck pulser, and the isolation transformer, with the interconnections between the elements.

3.2 *Operating Procedure*

The modulator can be operated installed in a transmitter, or independently for bench testing. The transmitter operating procedures may be more restrictive than the procedures described here.

The isolation transformer is required for operation in a transmitter, but may be omitted for bench testing. The floating deck may instead be connected directly to standard 120 VAC power.

The modulator can be operated with the outputs connected to a proper load, or unconnected.

Power may be applied to the floating deck and ground deck in any order, and fiber optic connections may be connected and disconnected with live power for bench testing. The input signals may also be connected or disconnected with live power for bench testing, The outputs from the floating deck are high voltage, so personnel should not be allowed near them while power is applied.

The preferred sequence of operation is as follows:

- Make all connections with power removed. Verify that the equipment is safe and secure prior to operation. Verify that the input pulse signal is off.
- Apply 120 VAC power to the ground deck pulser. Verify that the red (POWER) led lights, and the green (READY) led does not.
- Apply 120VAC power to the isolation transformer. Verify that the heater current and voltage meters rise and regulate as the cathode warms up. Verify that the positive and negative bias voltage meters indicate the proper voltages, and adjust the gate voltage control knob as needed. Verify that the green (READY) led lights.
- Once the voltages and currents have stabilized, the high voltage cathode supply can be energized according to the transmitter operating procedures. When the transmitter is ready, input pulse commands can be applied to the ground deck pulser.
- The sequence should be reversed for shutdown.

3.3 *Controls and Settings*

Several adjustments and controls are available to the operator. Some are used while the transmitter is operating, some are used to set the modulator for a specific tube, and some are used to set the protection limits and functions.

During operation, two controls are available:

- The pulse input is a real time 0/5V signal which defines the pulse train.
- The gate voltage adjustment dial is rotated clockwise to increase TWT beam current and the output RF power.

Two controls are available when power is applied to the modulator, but the cathode voltage is zero:

- A potentiometer accessible through a front panel access hole is used to adjust the heater voltage to match the TWT nameplate specification.
- A potentiometer accessible through a rear panel access hole is used to set the maximum duty cycle. This control should only be used with the grid output disconnected from the TWT to avoid damage to the grid.

The protection and regulation settings are made by hardware internal to the modulator. These are adjusted by jumpers or changing resistor values. The specific adjustments are described in the Theory of Operation section, but include:

- Maximum pulse width
- Fault latching / automatic reset
- Negative bias voltage level
- Heater current limit
- Pulse rise time

4 Theory of Operation

The solid state grid modulator comprises three major assemblies – The ground deck pulser, which serves as an operator interface, the isolation transformer, which provides high voltage isolation of 60 Hz power, and the floating deck pulser, which provides drive signals to the TWT grid and heater.

4.1 Ground Deck Pulser

The ground deck pulser, CPI PN 1152-2000, is a 2RU 19" panel with a circuit board on the back. It has a BNC pulse input, a voltage adjustment knob, and two status LEDs. The schematic, 1152 2000 Rev A, is supplied on CD-ROM with the unit, as are all other schematics. A ground deck pulser is shown in Figure 4-1.

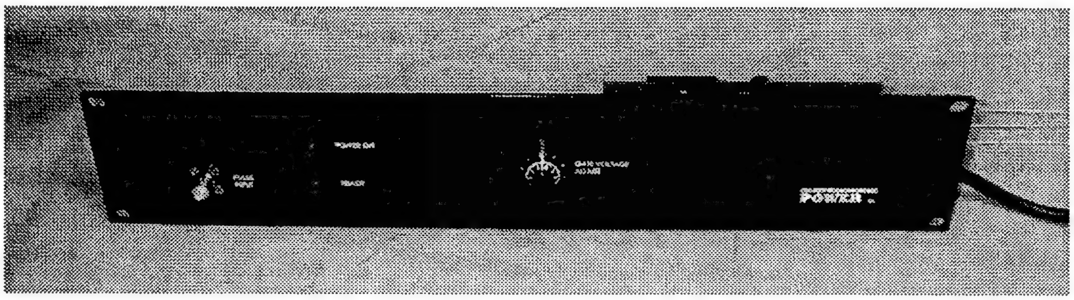

Figure 4-1. Ground Deck Pulser

The active circuitry for the ground deck pulser resides on the ground deck CCA, CPI PN 1152-2100. The CCA is assembled on a printed circuit board CPI PN 1152-2101.

The CCA includes a 120 VAC to 5 VDC converter, and a 5 to +/- 15 VDC converter.

A voltage to frequency converter U3 provides a frequency modulated pulse train to fiber optic transmitter U7. The frequency is controlled by the front panel knob, and is used to control the positive grid bias voltage. Turning the ten turn knob clockwise increases the frequency and the bias voltage.

A 5 volt pulse input command is received by U5, which drives fiber optic transmitter U8. A high impedance pull down resistor holds the signal off when no input is connected. No termination resistor is provided on the board.

A ready signal from the floating deck is used to drive a green LED. A red LED lights when power is applied to the board.

There are no hardware adjustments in the ground deck except for the front panel controls.

4.2 *Isolation Transformer*

Isolated 120 VAC power is provided to the floating deck pulser by a high voltage isolation transformer, shown in Figure 4-2 below. The transformer is a model AD-3069 from Del High Voltage, Valhalla, NY. It is rated at 500 VA and 50 kV isolation.

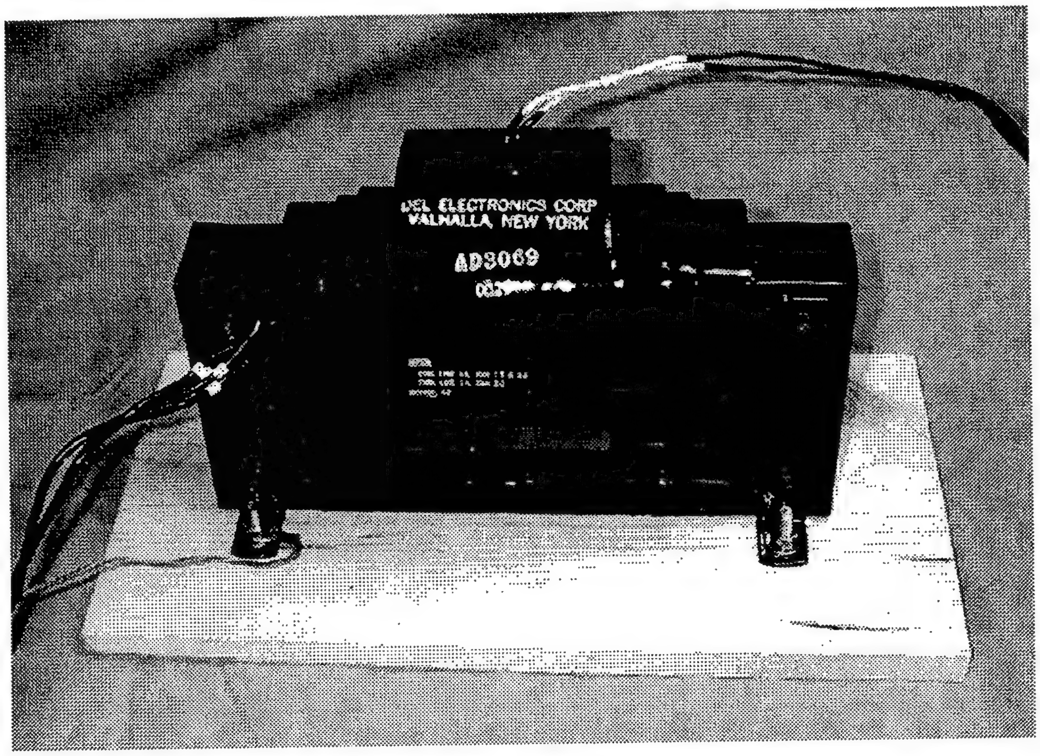

Figure 4-2. High Voltage Isolation Transformer

4.3 Floating Deck Pulser

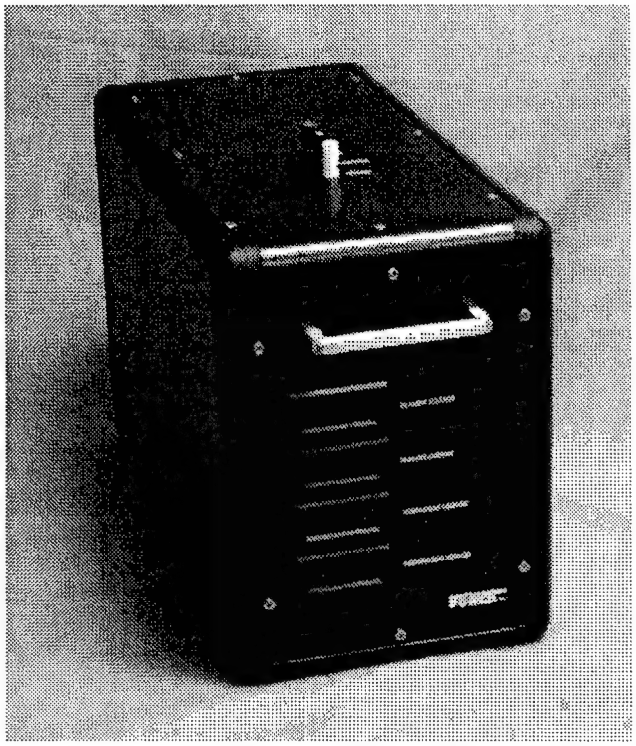

Figure 4-3 Floating Deck Pulser

Figure 4-3 shows a Floating Deck Pulser, CPI PN 1155-1000. Three terminals on top of the unit connect to the TWT cathode, heater, and grid. Four digital panel meters on the front show the heater voltage, the heater current, the positive gating voltage, and the negative grid bias. An access hole is provided to turn a potentiometer to adjust the heater voltage. Power and fiber optic signals connect to the rear of the unit. Screened vents allow air to circulate in and out of the chassis. Schematic 1152-1000 on the following page shows the design of the floating deck pulser.

The Floating Deck Pulser includes a power-factor corrected power supply which converts 120 VAC into 24 VDC to run the circuit boards, a regulator board which converts the 24 VDC into the voltages required by the pulser board and the heater, and a pulser board which generates the bias voltages and grid pulses. The Floating Deck also a spark gap, meters, and EMI filters.

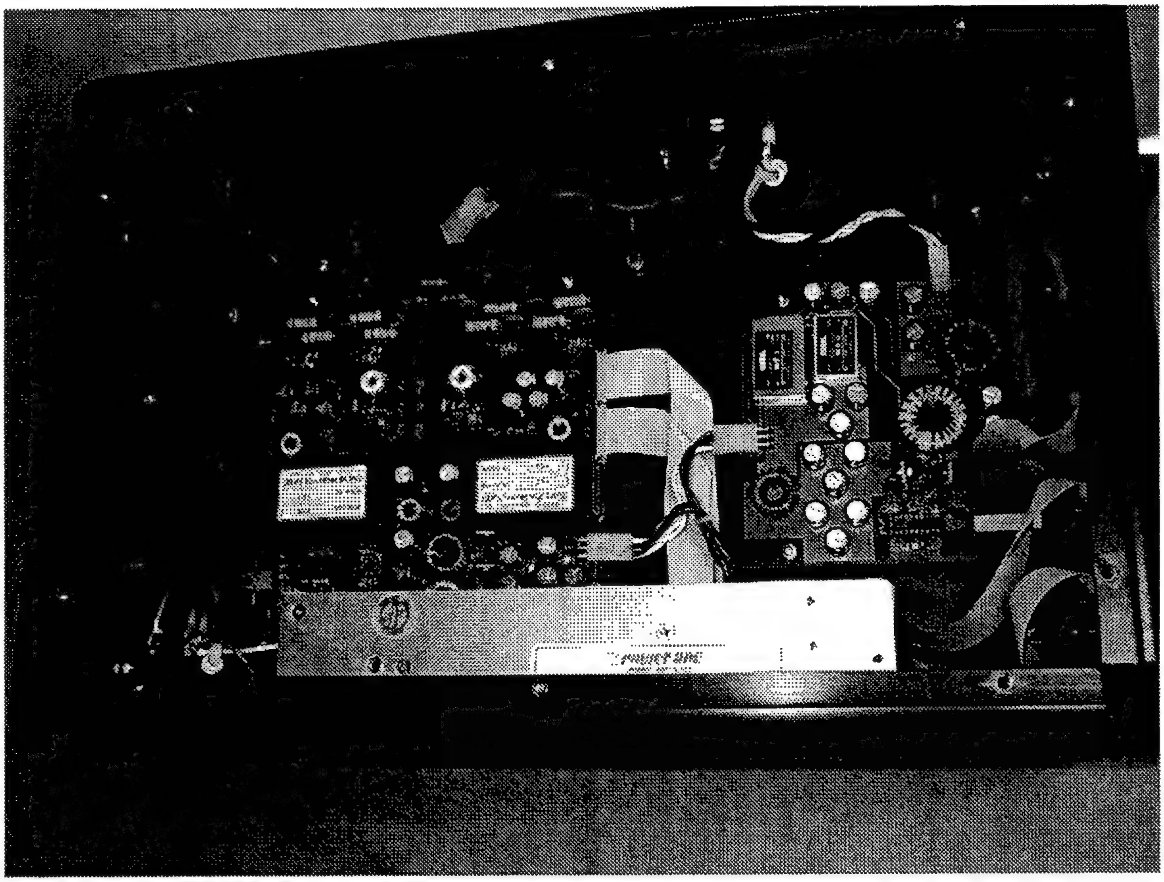

Figure 4-4. Inside View of Floating Deck Pulser

Figure 4-4 shows a Floating Deck pulser with the side cover removed. The power supply is at the base of the unit. The pulser board is on the left, and the regulator board is on the right. EMI filters are attached to the wiring at the back and top. Ribbon cables connect the boards to the front panel meters.

4.3.1 Pulser CCA

The Pulser CCA, CPI PN 1152-1100, receives input commands from the fiber optic cables, and provides output grid pulses. The schematic 1152-1100 Rev A is on the supplied CD-ROM. The CCA is assembled on a printed circuit board, CPI PN 1152 1101.

4.3.1.1 Pulser

The pulse command is received by receiver U3 at the upper left corner of page 1 of the schematic. The command is converted to a TTL level by U17, and anded with a ready signal which blocks all pulses unless all ready conditions are met. ON and OFF trigger pulses are created from the leading and trailing edges of the command pulse by one shot U11. The trigger pulses switch drivers U8 and U13, which pull current through pulse transformers T1 and T2 using transistor current amplifiers.

When T1 is driven with an ON pulse, current flows through diodes D4 and D8 to charge the gate capacitance of ON switch MOSFETs Q1 and Q2. The gate voltage is clamped by diodes D1 and D5. After the trigger pulse ends, the gate voltage is held up by the gate capacitance, together with C2 and C26. The bleeder current through R12 and R28 limits the maximum useful pulse width to about a millisecond.

When T2 is driven with an OFF pulse, Current is pulled through D1 and D5 to discharge the gate voltage of the ON switch MOSFETs, turning them off. At the same time, the gates off the OFF switch transistors are charged through diodes D17 and D18. Following the trigger pulse, the gate charge bleeds off through resistors R63 and R72. This bleed rate limits the maximum PRF to about 100 kHz.

The ON and OFF switches connect the grid to either the positive or negative supply voltage through a set of resistors, R48, R54, and R56. The value of R54 determines the grid voltage rise time. The other two resistors limit shoot through currents through the switches in case of faulty drive.

- The rise time of the output pulse can be decreased using a lower value of R54, or increased with a higher value

The resistor and capacitor networks across the switches serve two purposes. They dynamically balance the voltage across the MOSFETs so that voltage is shared equally, even if there are minor differences in the switching times of the devices. Also, the lower valued resistors across the bottom switches maintain negative bias on the grid after the OFF switch gates have discharged.

4.3.1.2 Bias Supplies

The positive bias supply is shown on the top half of page 2 of the schematic. A frequency modulated command signal is received by U1. This commands the positive bias level. A frequency to voltage converter, U6, converts the signal to a command voltage level.

The positive bias voltage is monitored by op amp U9, which provides a feedback signal to the buck converter. The op amp compares the positive bias voltage to the voltage received from the frequency to voltage converter, and produces an error signal.

This signal is combined with a sample of the DC link voltage. If the feedback to U14 exceeds 2.2 volts, U14 reduces its output voltage. This regulation scheme combines a fast response inner loop regulating the DC link with a slower outer loop which regulates the bias voltage.

U14 is a single switch buck converter chip. It converts 24 volt input power to 0-12 volts, working with diode D15 and inductor L4. The 0-12 volts is filtered by L2, C40, and C41. U5 includes a chopper and a multiplier, and converts the 0-12 volt input to 0-600 VDC. L1 and a capacitor network filter the output to attenuate ripple.

The negative supply, shown on the bottom of page 2, is similar to the positive supply, except that the outer loop is omitted. The output voltage is fixed. It is determined by the value of the feedback resistor.

- The negative bias voltage can be increased by increasing the value of the 13.5k resistor.

4.3.1.3 Protection

A number of protection functions are combined to make the READY signal which determines whether the pulser will accept a pulse command. If any of the protection conditions is not satisfied, the pulse will be blocked or terminated.

U12, at the bottom left of page 2, monitors the system voltages and provides a POWER OK output. It monitors the +5 and +/-15 volt lines directly. It also monitors the negative bias supply indirectly by looking at the feedback line. If the negative bias voltage is present the voltage will be 2.2 volts, or higher if the voltage is above the regulation point. If the bias voltage is below the regulation point, the voltage will be below 2.2 volts. A fault is declared if any of the four voltages is below its threshold.

U4D at the left side of page 1 monitors the actual grid voltage to determine if the average voltage is low enough. As the duty cycle increases, the average voltage increases. Also, a loss of negative bias or grid short will trip this gate. Capacitor C13 sets the time constant, to average out the pulse waveform. R5 is used to adjust the trip level.

U7 and U10 monitor the commanded pulse width, and declare a fault if the pulse is too long. At the start of each pulse, one shot U7A provides a 1 millisecond output. At the end of 1 millisecond, if the pulse command is still present, U10A latches in a fault. The 1 millisecond pulse is retriggered each time a new input pulse is received, so it will not trip on a train of short pulses. The length of the maximum pulse is set by R25 and C21.

- Change R25 for small adjustments in the maximum pulsewidth. Change C21 for large adjustments.

When a fault is declared by U10, U7B is triggered to automatically clear the fault after a delay time. The delay time is set by 21 and C24.

- Change C24 to set the delay time before a fault is reset.
- The automatic reset function can be disabled by moving R32 from pin 8 to +5V.

If all protection functions are satisfied, driver U2 sends a READY signal to the ground deck pulser.

4.3.2 Regulator CCA

The Regulator CCA, CPI PN 1152-1200, converts 24 VDC power into +5 and +/-15 VDC power for the pulser board, and provides regulated voltage to the heater. The Regulator CCA is built on a printed circuit board, CPI PN 1152-1201.

The 5 VDC output is derived from the 24VDC input by U2, which is a 3 watt DC/DC converter. The +/-15VDC outputs are provided by U1, which is a 6 watt converter. The outputs are referenced to the heater terminal, which is connected to the 24 VDC return, rather than the cathode, which is connected to the chassis. This is done to simplify the heater regulator.

The heater voltage is controlled by a buck converter with synchronous rectification. MOSFETs Q1 and Q2 act as a buck converter with inductor L2. LC filters before and after the converter attenuate ripple.

U3, a Linear Technologies LT 1339, is a specialized controller for this type of converter. It incorporates a variety of protection and compensation techniques for robust operation. It has undervoltage detection, slope compensation, and current limiting functions built in.

Resistor R13 is a current sense resistor. It is used to limit the maximum short circuit currrent by restricting the voltage drop to .120 volt. A resistor value of .010 ohms gives a nominal current limit of 12 amps. Resistor R15 is used to trim the current limit by dividing the signal down in conjunction with R6 and R8. The 2k value installed provides a nominal current limit of 13.2 amps. A smaller value for R15 gives a higher current limit.

- Make small adjustments in the current limit by reducing R15 to raise the current limit. Make larger changes by changing R13.

Op amp U4 is a differential amplifier which provides a 0-15 volt signal to a front panel meter. The signal is proportional to the output current. A second meter monitors the output voltage directly.

5 Test Results

Each circuit board was individually tested for functionality prior to installation in a modulator. Following unit test, the boards were swapped to verify that they were interchangeable among units.

Each unit was checked for proper regulation of voltages under various load conditions, including no load, full load, and short circuit. Thermal tests were run on the first unit to verify that the steady state temperatures under worst case conditions were within acceptable limits. The units were subjected to improper input and output conditions to verify that the protection functions were operating properly.

The modulator is required to provide pulsewidths from 1.4-300 microseconds, at Pulse Repetition Intervals down to 35 microseconds, at a duty cycle of up to 6%.

Figure 5-1 shows an output pulse of 1.2 microseconds. Figure 5-2 shows an output pulse of <500 nanoseconds.

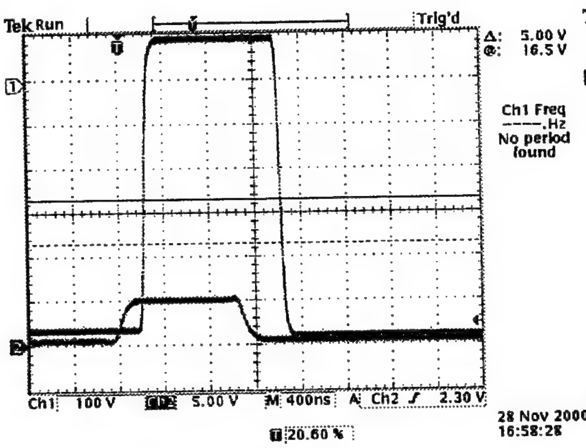

Figure 5-1 1.2 Microsecond Pulse

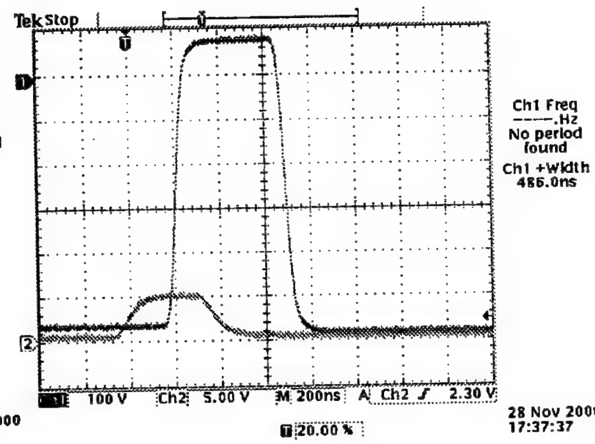

Figure 5-2 500 Nanosecond Pulse

Figures 5.3 and 5-4 show the rise and fall times of the pulse, along with the delay time from the input to the ground deck to the output of the floating deck.

Figure 5-5 shows a train of pulses at 38 kHz, with a Pulse Repetition Interval of 25.8 microseconds.

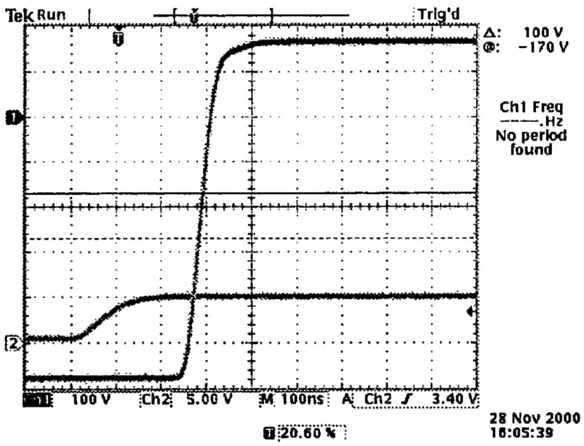

Figure 5–3 **Pulse Rise Time and Delay**

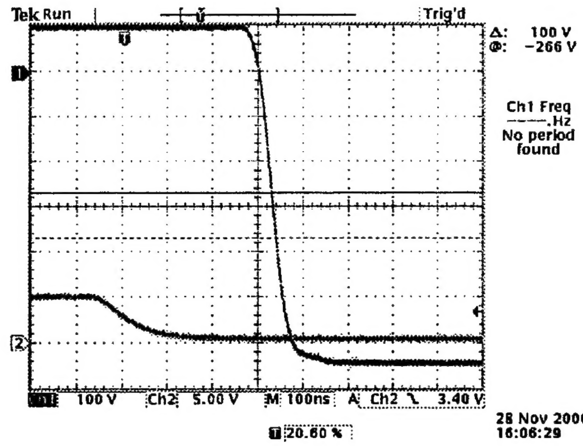

Figure 5–4 **Pulse Fall Time and Delay**

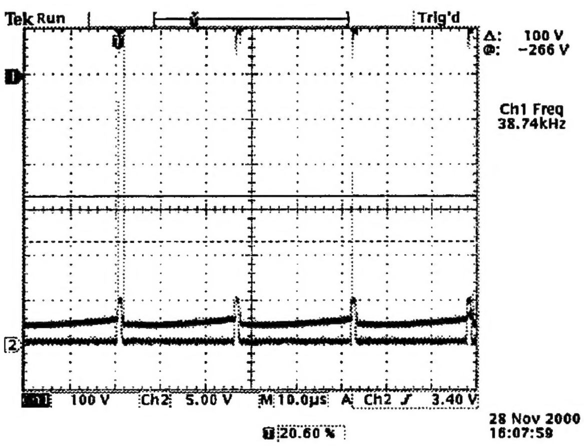

Figure 5–5**. 38.75 kHz PRF, 25.8 Microsecond PRI**

Figures 5-6 through 5-19 on the following pages show pulses ranging from 2-300 microseconds, at PRFs from 200 Hz to 32 kHz.

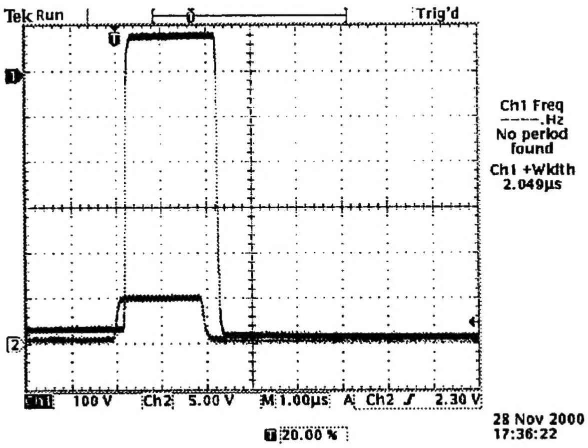

Figure 5-6. **2 Microsecond Pulse**

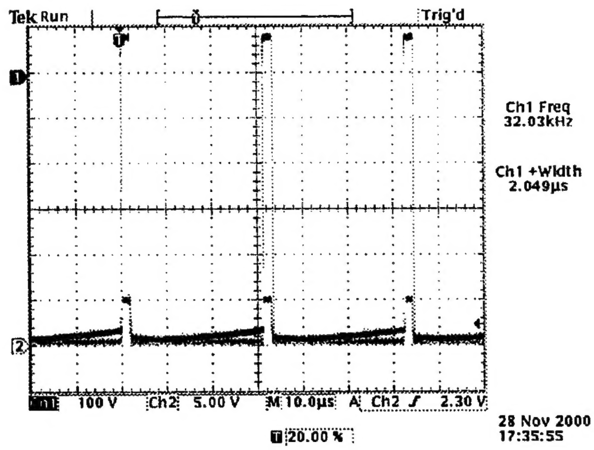

Figure 5-7. **32 kHz PRF**

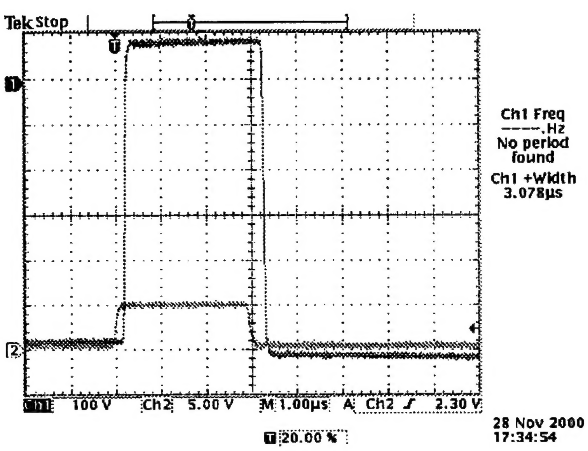

Figure 5-8 **3 Microsecond Pulse**

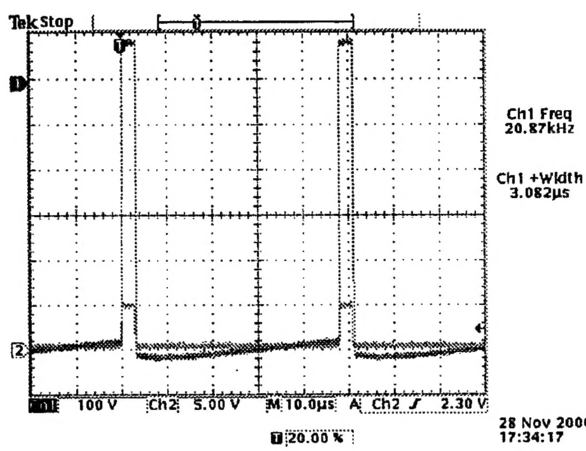

Figure 5-9 **20 kHz PRF**

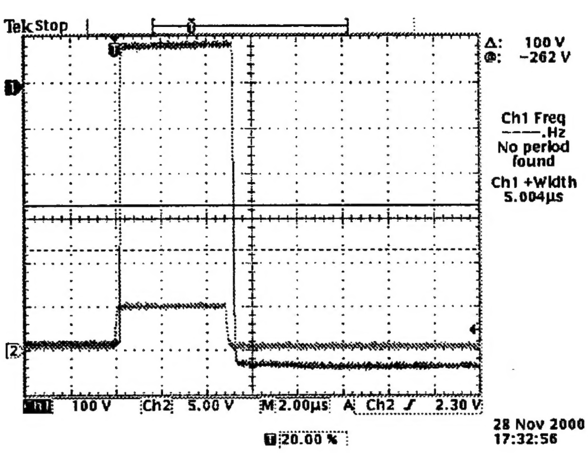

Figure 5-10 **5 Microsecond Pulse**

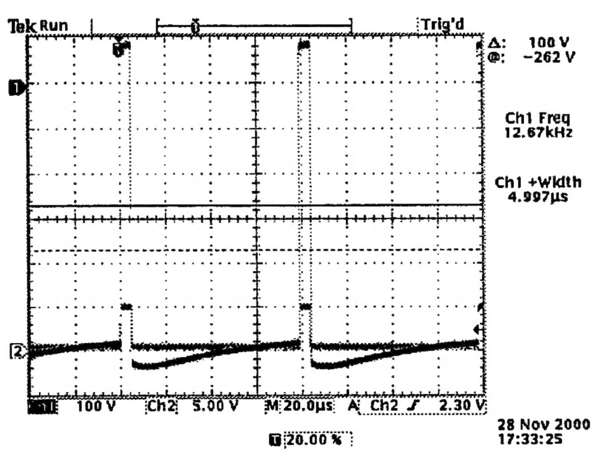

Figure 5-11. **12 kHz PRF**

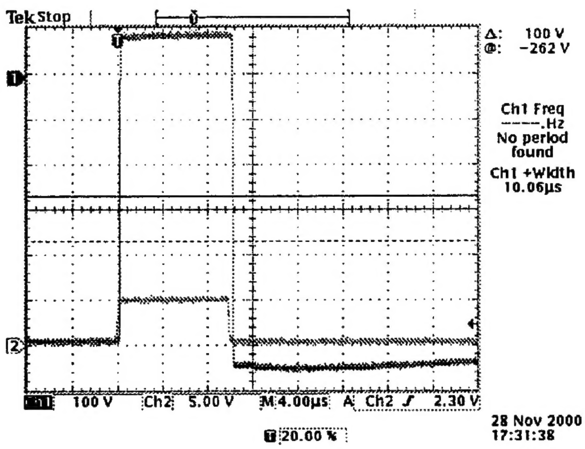

Figure 5-12, **10 Microsecond Pulse**

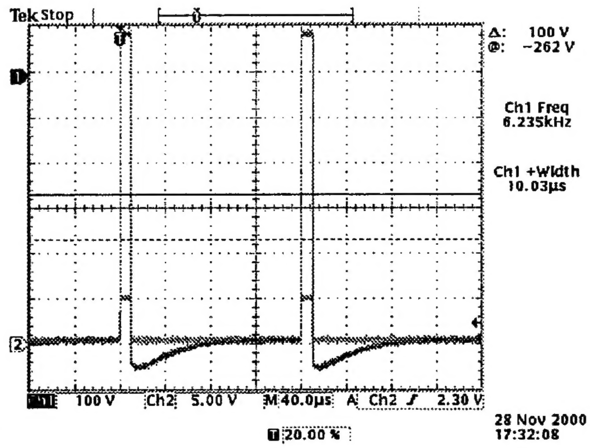

Figure 5-13. **6 kHz PRF**

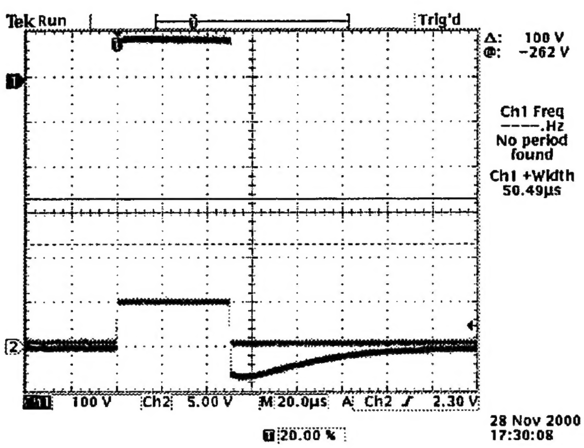

Figure 5-14 **50 Microsecond Pulse**

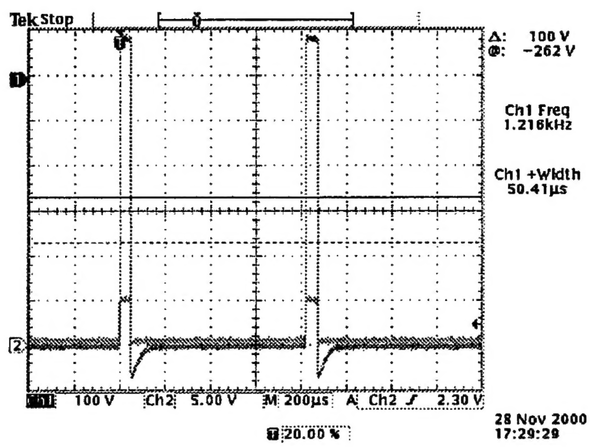

Figure 5-15 **1.2 kHz PRF**

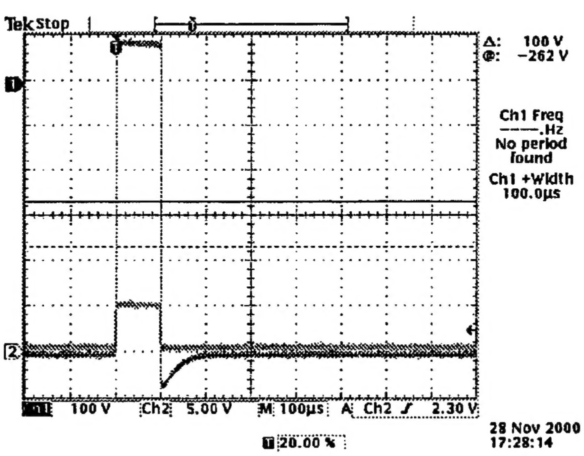

Figure 5-16. **100 Microsecond Pulse**

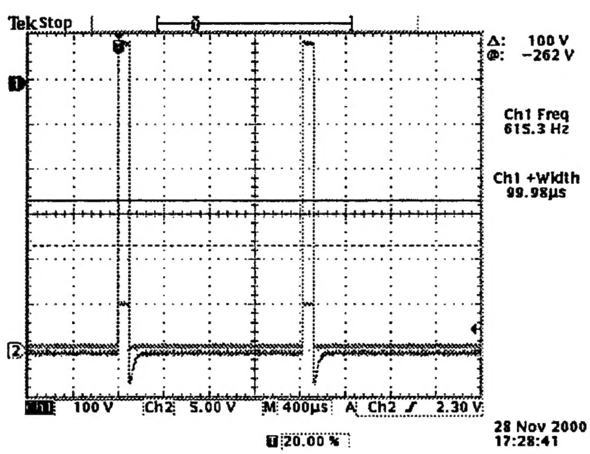

Figure 5-17. **600 Hz PRF**

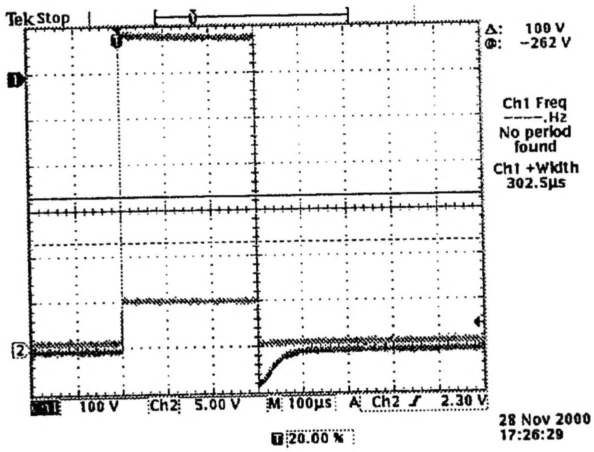

Figure 5-18. **300 Microsecond Pulse**

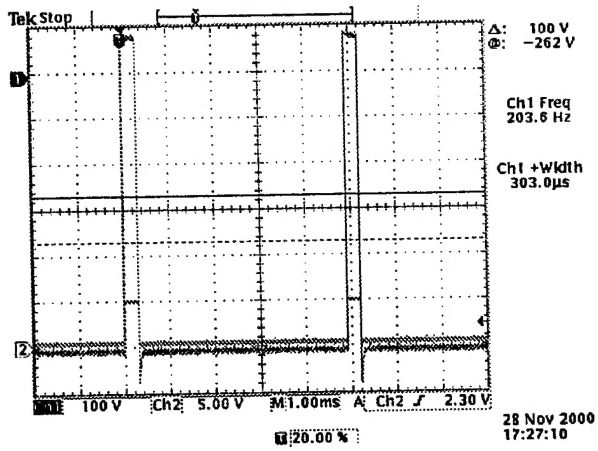

Figure 5-19. **200 Hz PRF**

6 Conclusions

The Solid State Grid Modulators were successfully designed, fabricated, and tested. Two modulator systems, plus a spare ground deck and floating deck have been delivered and tested at the Rome research site. The modulators meet all of the specified requirements, providing a wider range of pulse widths and PRFs than needed at the present time.